RADIO Detection of UHECRs

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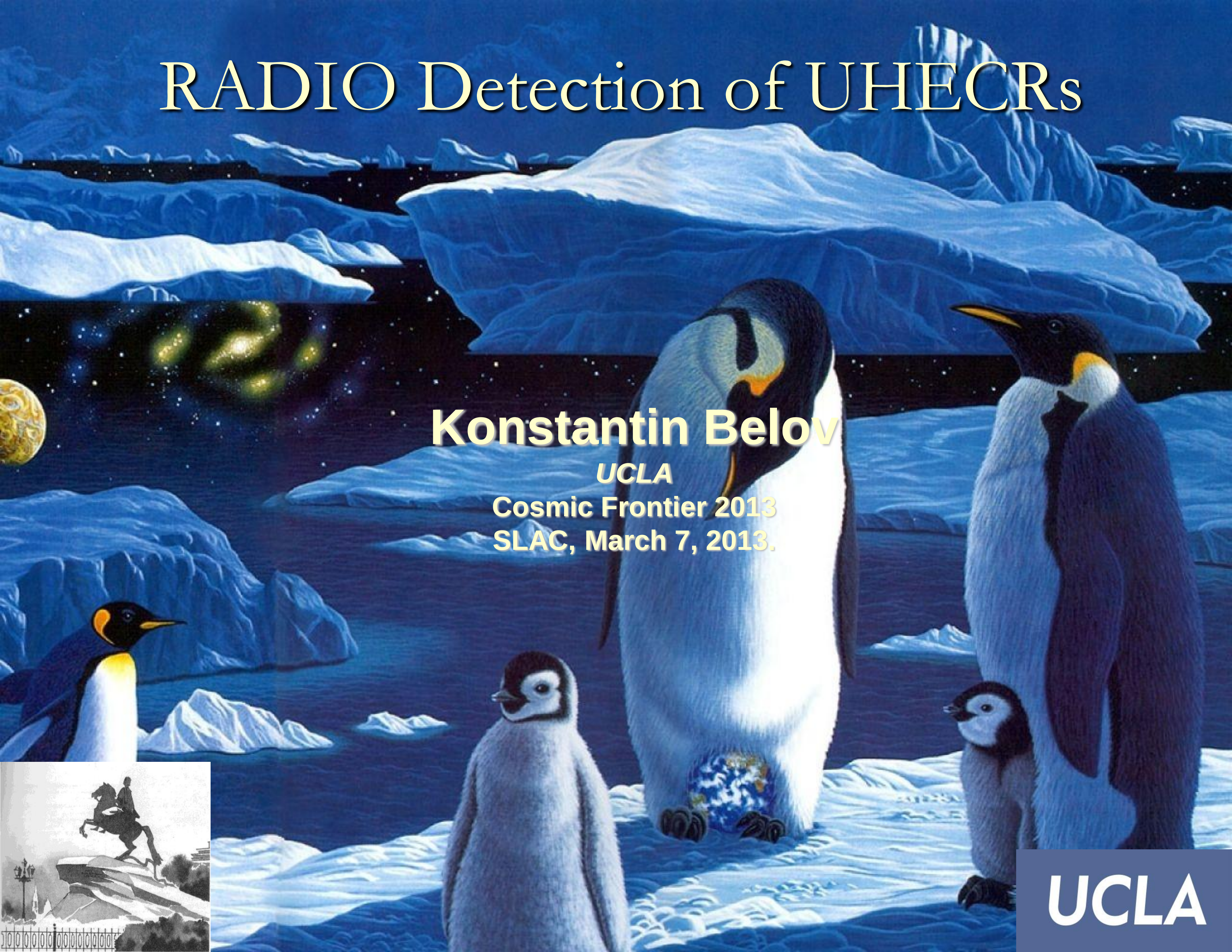
UCLA

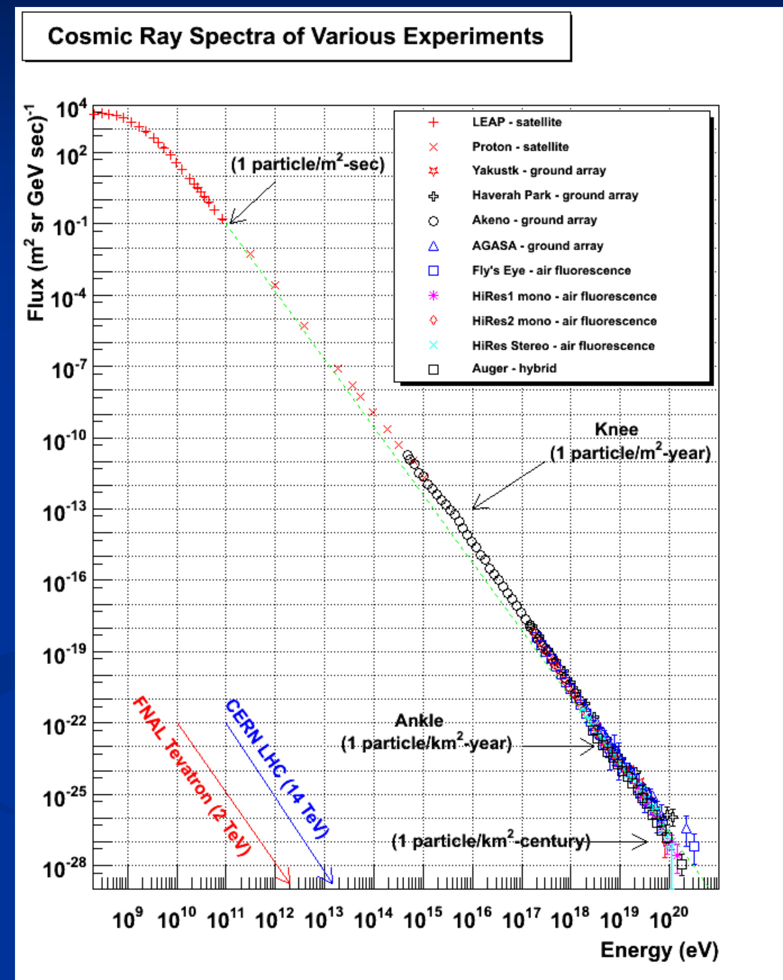
Cosmic Frontier 2013

SLAC, March 7, 2013.



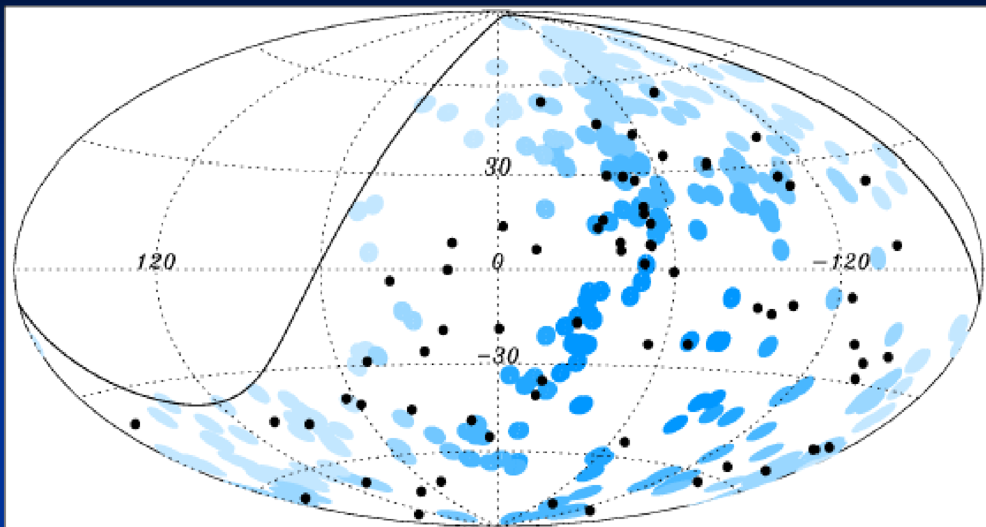
Why ultra-high energy cosmic rays (UHECR's)?

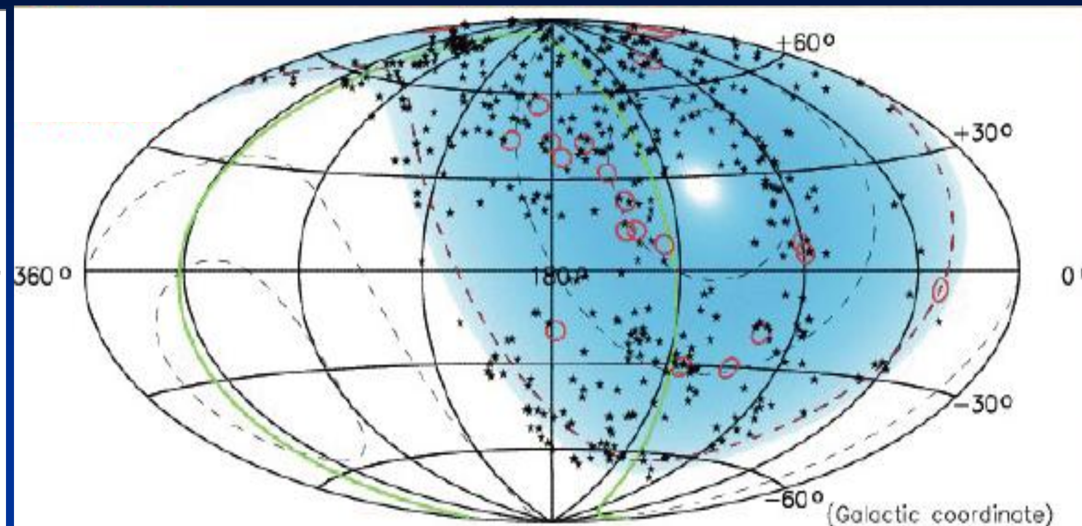
- Ultra-high energy particle astrophysics is a new, non electro-magnetic "window" into the Universe.
- Information about hyper-powerful particle accelerators can indicate new physics
- After decades of research, the origin and acceleration mechanism of the ultra high energy cosmic rays (UHECRs) are still unknown
  - Nearby sources of UHECRs are excluded based on observational data
  - Distant sources are excluded due to proton photo-disintegration on CMB (GZK mechanisms)
- Trajectories of charged particles are deflected by the magnetic field
  - Only highest energy particles can point back to their origin



Plot by W. Hanlon based on S. Swordy's plot

UHECR Astronomy ?





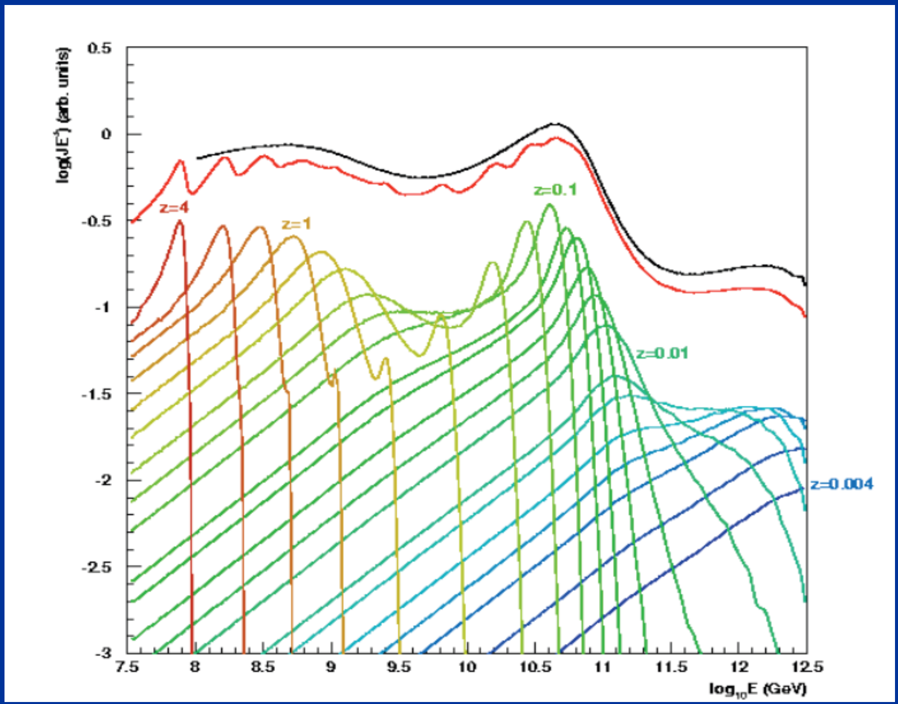
Black dots - arrival direction of 69 Auger events with E > 55 EeV
Blue - 3.1 degree circle around 318 AGN's from VCV catalog
arXiv:1009.1855v2 [astro-ph.HE] 29 Sep 2010

Red: 20 TA events with E > 57EeV
Black: AGNs closer than 75Mpc
ICRC 2011

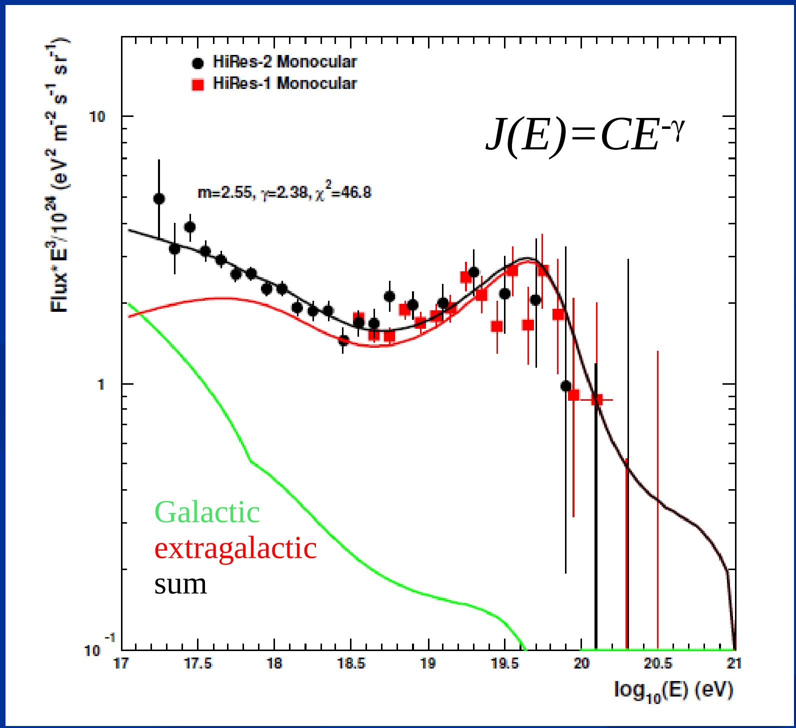
- A correlation of the arrival directions of the UHECR's with AGN's reported by the Auger collaboration (*Astropart. Phys.* 29 (2008) 188-204) – more data is needed.
- TA and earlier HiRes did not see any correlation

Still learning about the sources of the UHECRs

- **Spectrum and composition of the UHECRs can provide information about the sources and their evolution**
  - **Fit to extragalactic sources ~ $(1+z)^m$, where m is called the evolution parameter**



Contribution from sources in slices in redshift to the energy loss model for extragalactic uniform source model (USM) with $\gamma = 2.4$, m=2.5. D. Bergman, ICRC2005, 7 315.



Best fit to the HiRes monocular data. USM+Galactic $\gamma = 2.38$, m=2.55.
D. Bergman, ICRC2005, 7 315.

Greisen–Zatsepin–Kuzmin (GZK) mechanism

$$p + \gamma_{6K} \rightarrow \Delta^{*} \rightarrow n + \pi$$

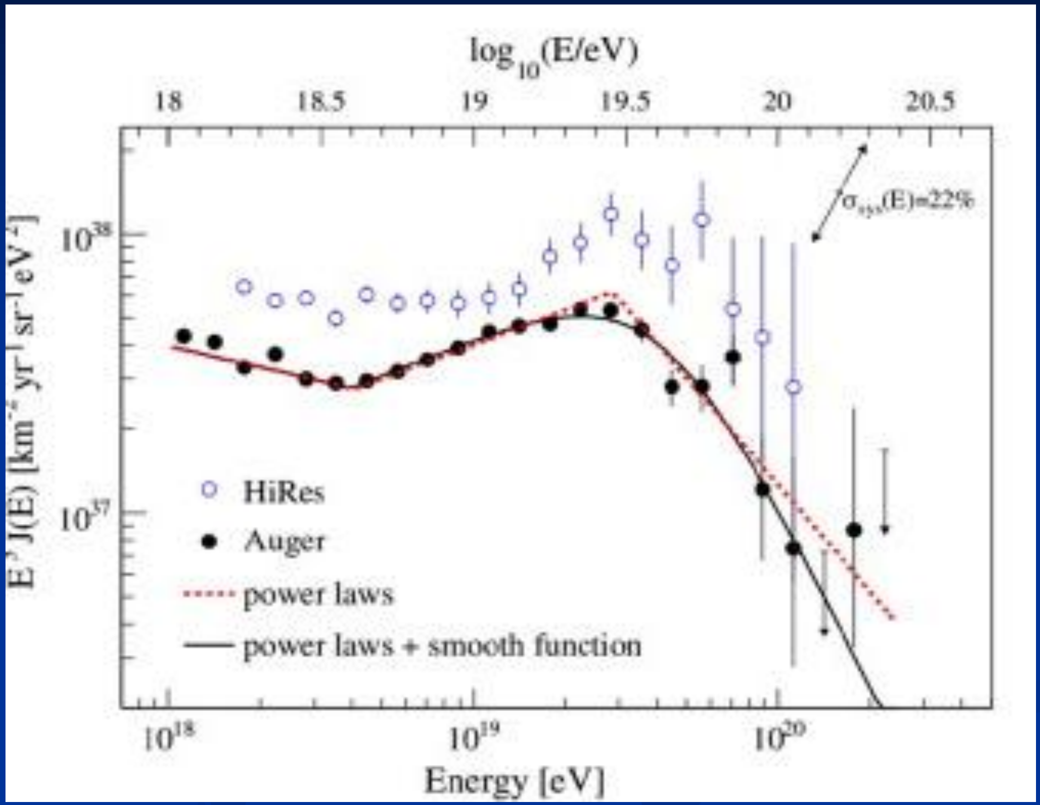
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu} \ (99.9877\%)$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$$

$$Fe + \gamma_{6K} \rightarrow 26 \times p + 30 \times n$$

$$30 \times n \rightarrow 30 \times (p + e^{-} + \overline{\nu}_{e})$$

CMB is 6K at z=1

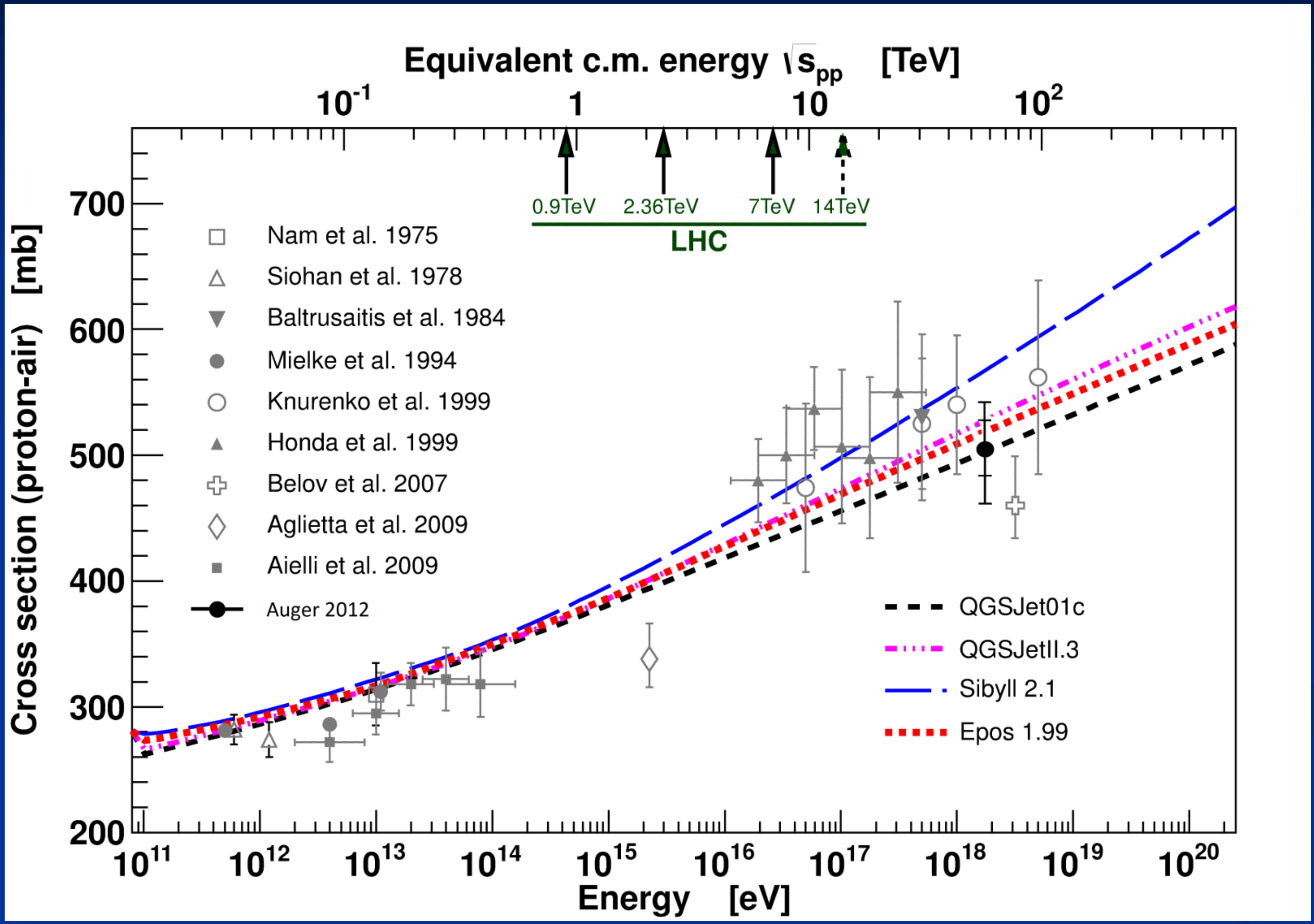


Plot by P. Sommers, Astropart. Phys. (2012)
Spectrum from:
The Pierre Auger Collaboration, Phys. Letters B685 (2010) 239.
R.U. Abbasi et al., Astropart. Phys. 32 (2009) 53.

Other sources of UHECRs

Exotic top-down models:
- Z-bursts
- Magnetic monopole decays

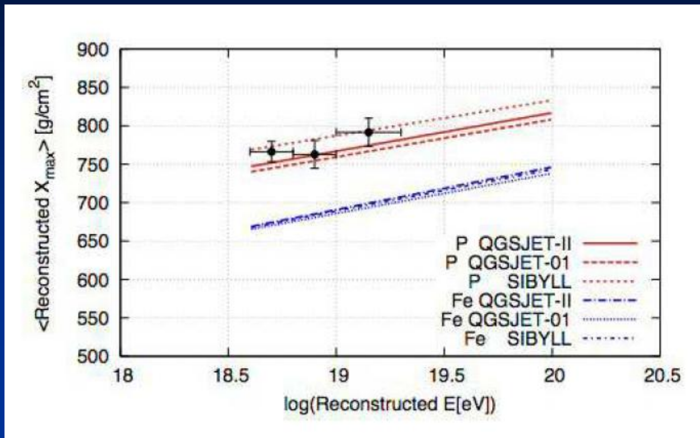
Particle interactions at ultra-high energies



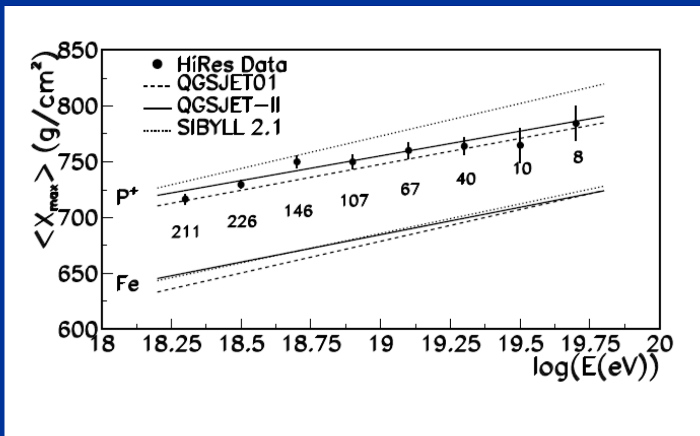
Proton-air inelastic cross-section measured by accelerators and cosmic-ray experiments.

Color lines – different interaction models and accelerator data extrapolation.

UHECR composition

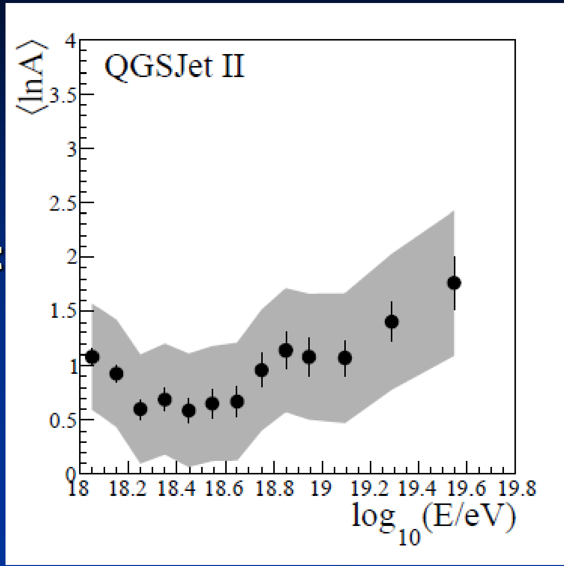


J. Matthews, Nuclear Physics B - Proceedings Supplements Volumes 212–213, March–April 2011, Pages 79–86

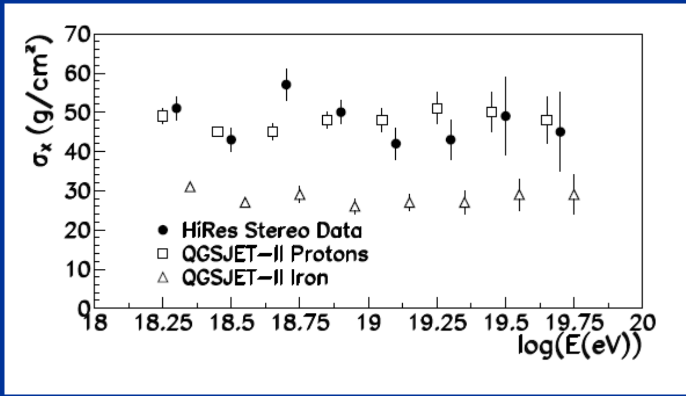


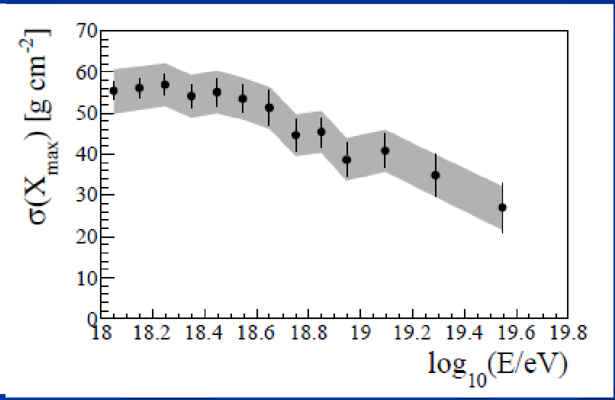
P. Sokolsky, Nuclear Physics B - Proceedings Supplements Volumes 212–213, March–April 2011, Pages 74–78

- Preliminary data from TA (upper left) and Previous HiRes result (lower left) do not indicate heavier components at high energies
- Recent Auger data indicates heavier composition (right plot)



Pierre Auger Collaboration, Jan. 2013, arXiv:1301.6637

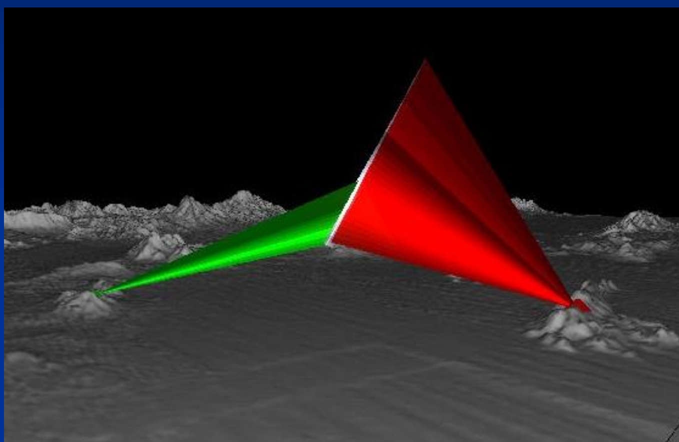




- No agreement on dispersion of the X_{max} distribution is an indication of the detector bias?

Air fluorescence

Hires stereo air fluorescence detector in Dugway Proving Ground, Utah 1999-2006



Picture by W. Springer

Camera. 256 PMTs

HiRes building with two mirrors

PMT

Pros:

- **Energy measurement is calorimetric**
  - **Calibration is very well understood:**

  Ionization loss => trackleight =>fluorescent emission

Cons:

- **10% duty cycle**
- **Aperture is difficult to estimate:**
  - **Energy dependence**
  - **Atmospheric monitoring required (radiosondes, IR cloud monitoring etc)**

HiRes2 detector

Two detectors, 62 mirrors x 265 PMTs = 15872 PMTs

K. Belov UCLA

Ground counter arrays

AGASA, Japan, 1991-2004
100 km2 area

PMT is still the King

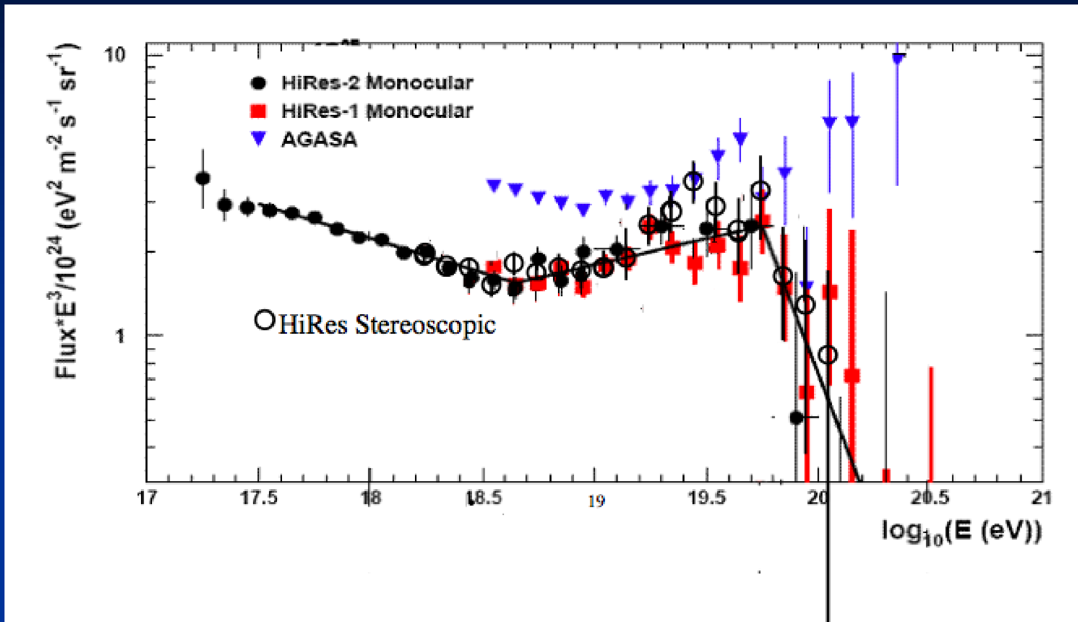
Pros:

- **100% duty cycle**
- **Exposure is easily estimated**
- **trigger efficiency is 100% for large showers**
- **self-calibration with atmospheric muons**

Cons:

- **energy measurement relies on MC simulations**
- **Assumed hadronic interaction model requires extrapolations of collider data to higher energies and rapidities.**
- **difficult to estimate uncertainties.**

Energy spectrum discrepancy

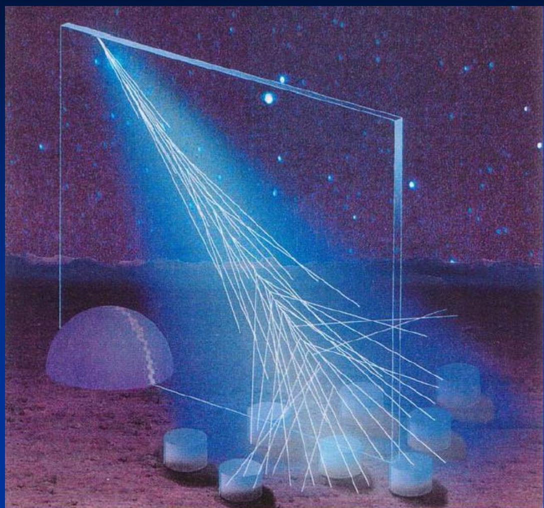


P.Sokolsy, Final Results from the HiRes Experiment SLAC, 2009

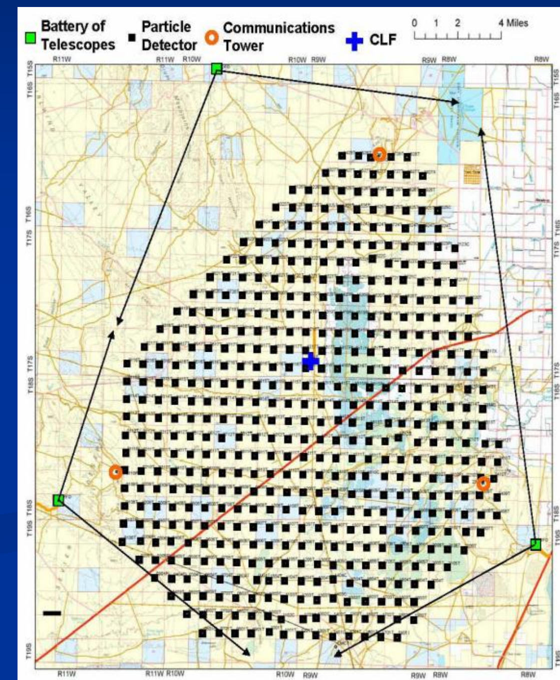
- **Significant differences in spectrum measurements between a ground array and an air fluorescence detector**
- **The absence of the GZK cutoff observed by AGASA is not confirmed by HiRes**

Logical next step is to combine the observation techniques

Hybrid Cosmic Ray Detectors



TA hybrid detector.
1600 ground counters
3 air fluorescence telescopes
+ TALE – low energy extension



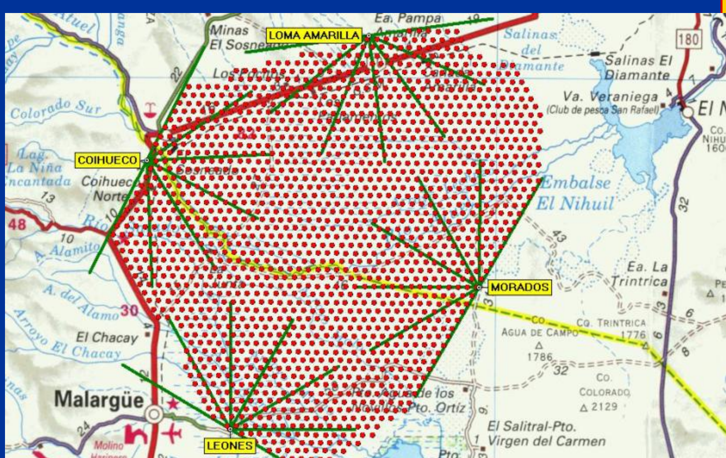
Best of both approaches:

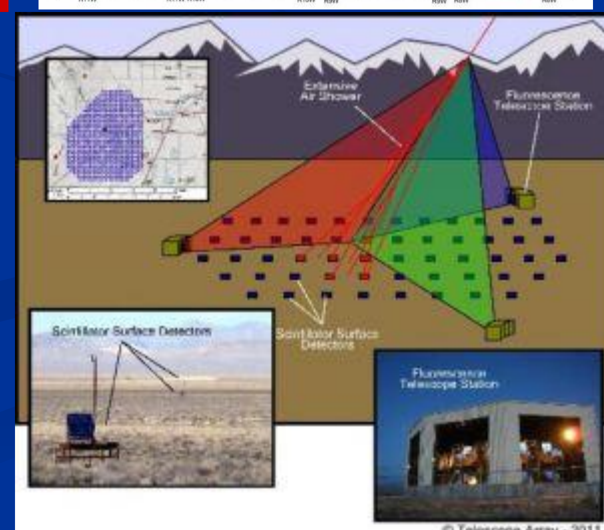
- **Energy is calibrated using FD**

Comes at a cost:

- **Two costly detectors have to be built**
- **Significant deployment and operation costs**

Auger hybrid detector.
1600 water tanks
4 air fluorescence telescopes





Radio emission from Extensive Air Showers

- **Radio is an attractive observation technique:**
  - **100% duty cycle**
  - **Lower deployment and operational costs**
  - **Atmospheric conditions do not affect aperture**

Frank-Tamm power spectrum:

$$\frac{d^2W}{d\nu dl} \propto z^2\nu \propto E^2{}_{primary}$$

For coherent radio emission

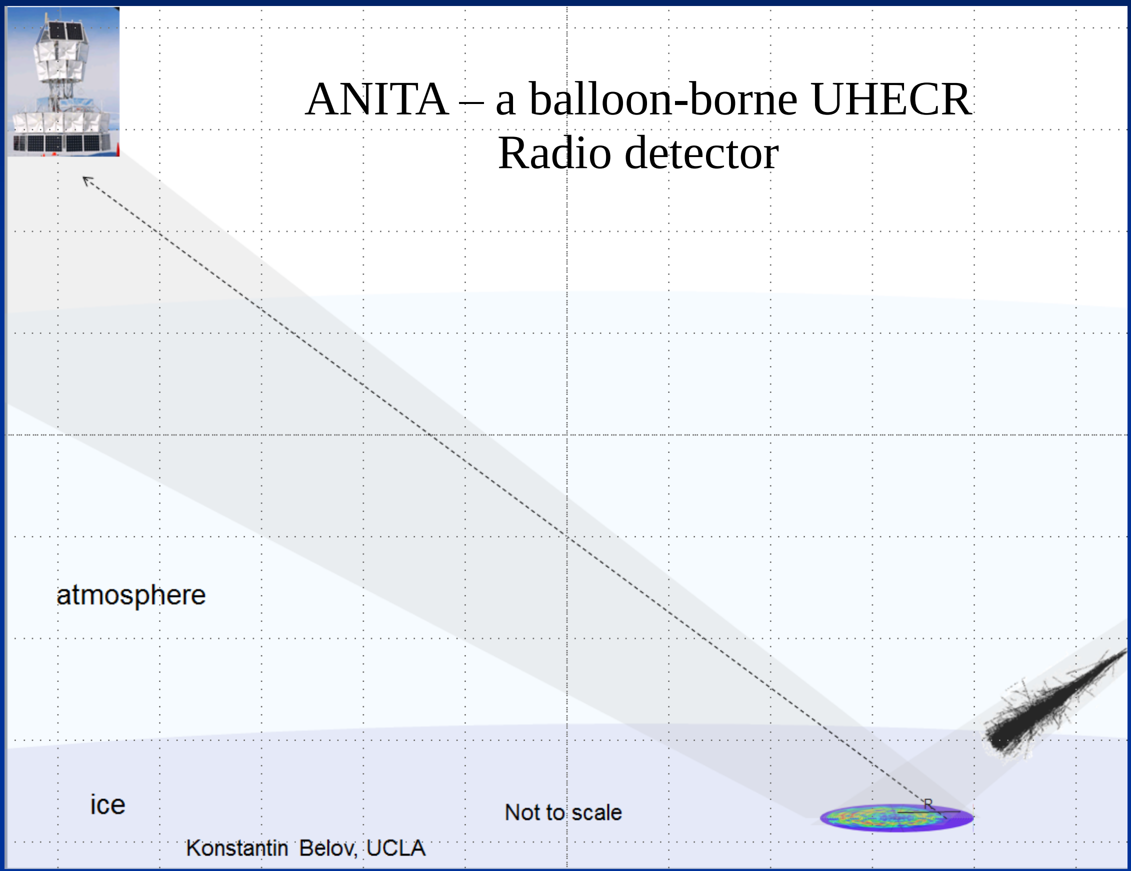
Cherenkov light is emitted into the cone with

$$\cos\theta_C = 1/\beta n$$

For Extensive Air Showers:
- Typical size ~ km
- Coherent emission is up to ~ 10 MHz
- Power emitted in radio is not significant ?

In Dense Media:
- Typical size < 1 m
- Coherent emission is up to ~ 1 GHz
- Power emitted in radio is significant

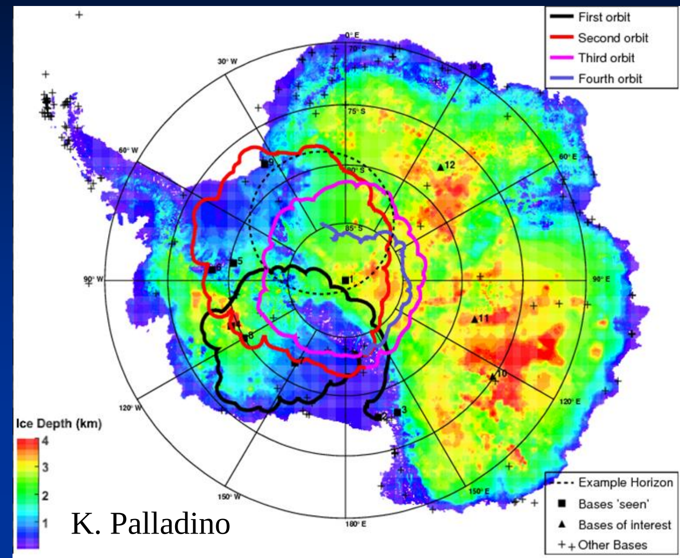
Balloon-borne detector



- **16 UHECR events observed during ANITA I flight**
- **Energies of the events reconstruct ~ 10^{19} eV**
- **X_{max} measurements are difficult by a balloon experiment**
- **ANITA II did not trigger on H-pol**
- **ANITA III will have highly upgraded H-pol**

ANITA I – Dec 15, 2006 – Jan 19, 2007


Picture by James Roth



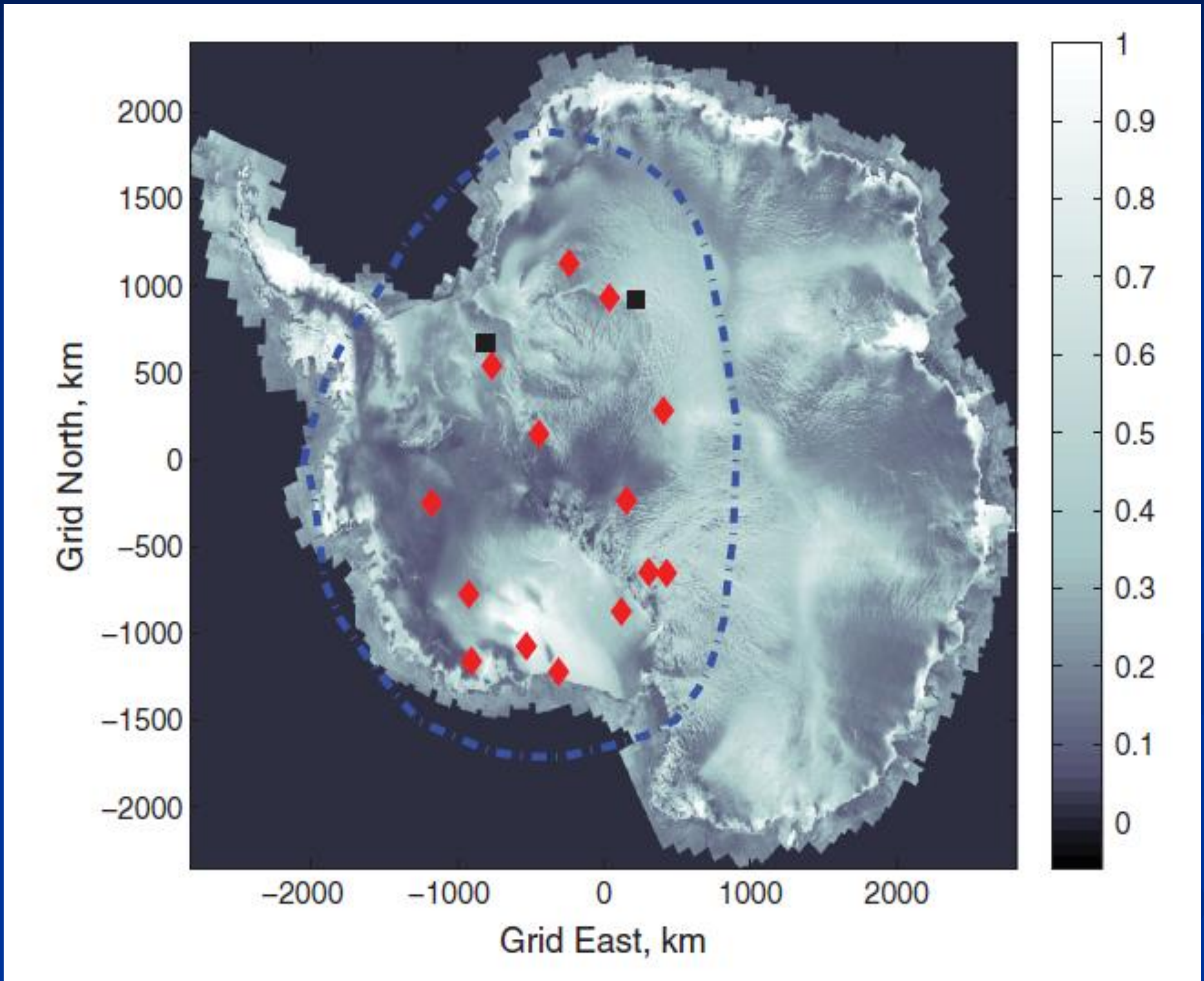
K. Palladino

- 32 quad-horn antennas sensitive to V and H polarization
- 200-1200 MHz band
- L1 trigger:
  - 4 frequency bands in both LCP and RCP for trigger
  - 3/8 channels to form L1 trigger
- L2 trigger 2/3 adjacent antennas
- Upper and lower ring to form L3 trigger


D. Braun

K. Belov UCLA

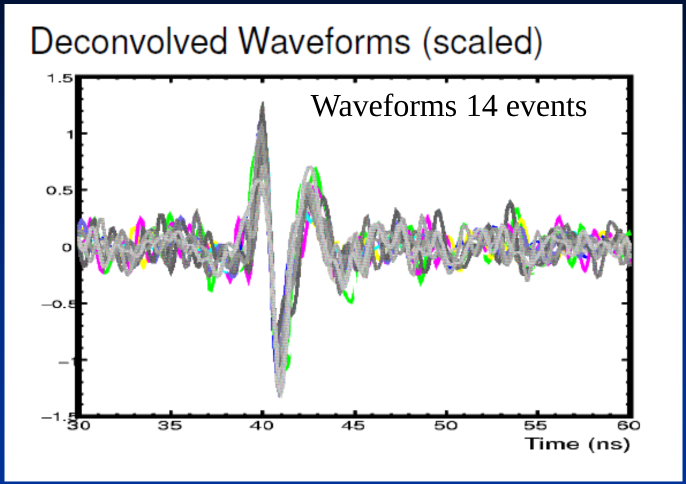
ANITA Data analysis reveals 16 isolated H-pol events

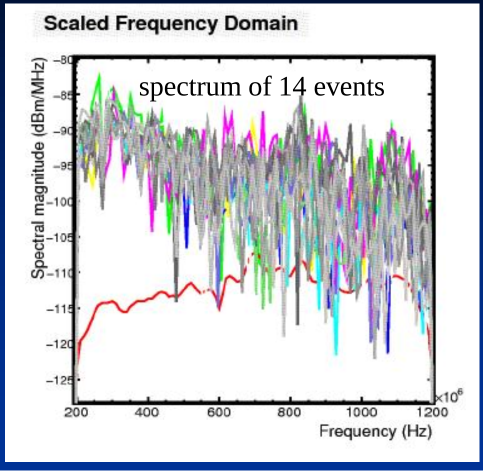


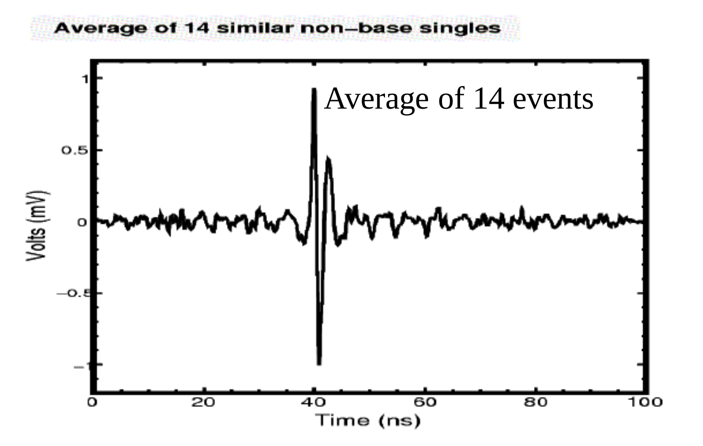
S. Hoover, J. Nam, P.Gorham et al.
PRL 105, 151101 (2010)

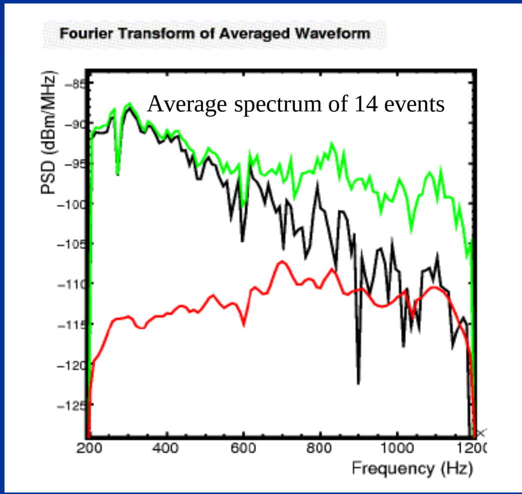
16 non-base single events
14 similar to each other in shape and spectrum
H-pol and impulsive with very weak V-pol content

H-pol events waveform and spectra









S. Hoover CR analysis

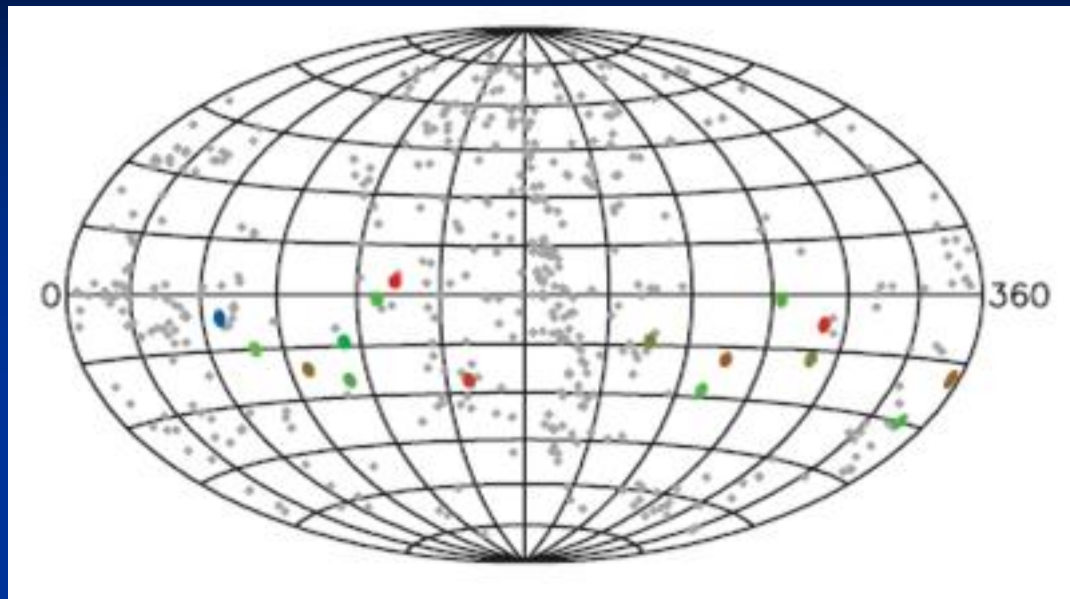
Green – individual power spectra averaged

Black – power spectrum of averaged wave form

Red – noise power spectrum

- Similar waveform and spectra
- Same polarity for 14 events (up, down, up again) - reconstructed on the ice
- The other 2 events are very similar, but have the opposite polarity – reconstructed above the horizon!
- Measured V-pol content correlates with predicted from geomagnetic field
- Geosynchrotron mechanism is dominating the RF emission

If they are UHECR, do they point back somewhere?



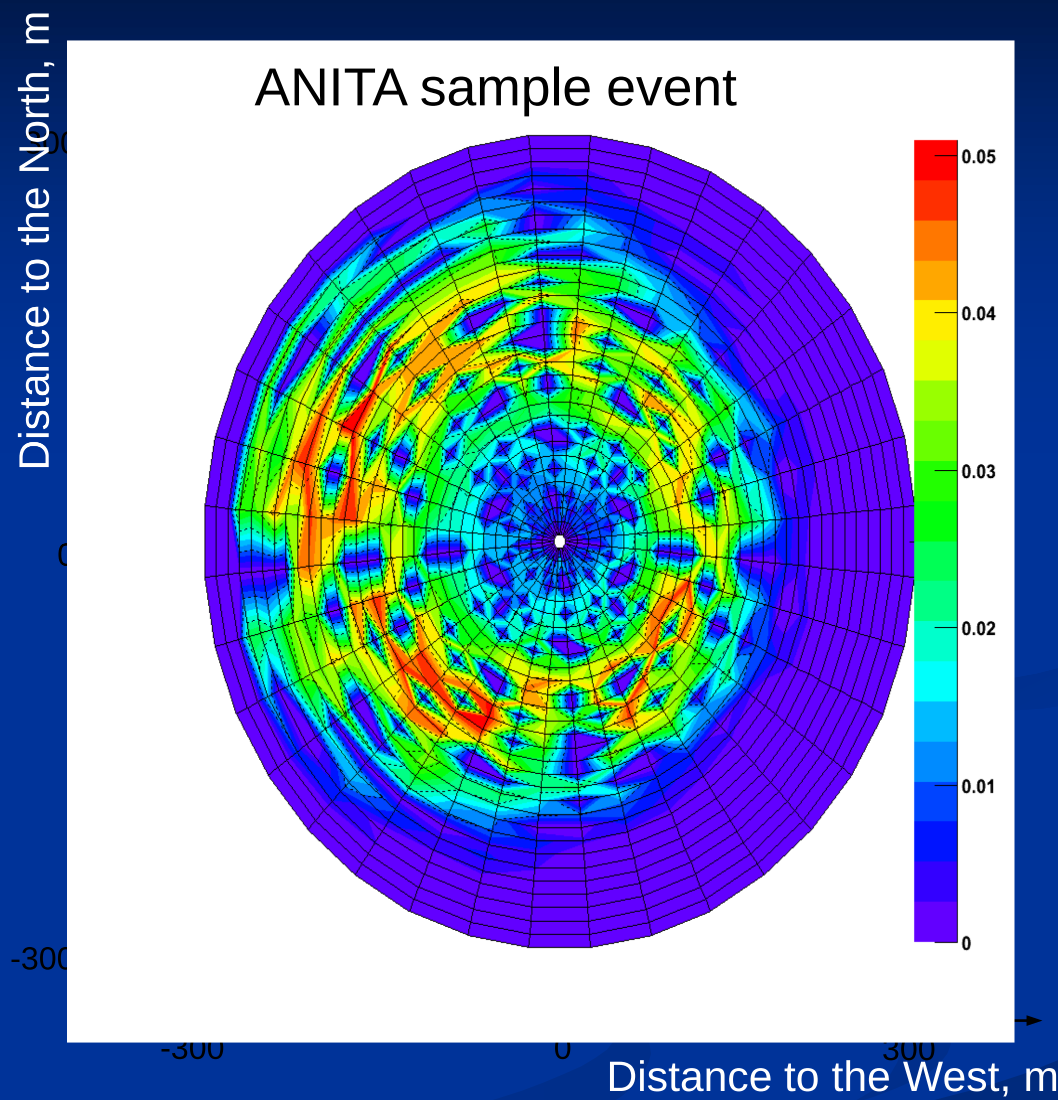
S. Hoover, J. Nam, P.Gorham et al.
PRL 105, 151101 (2010)

- ANITA events with ~ 2 degree circle as pointing error
- Gray diamonds – AGNs from Veron-Cetty.
- A statistical analysis showed no correlation

Can we reconstruct the energy from radio data only?

ANITA sample event simulated

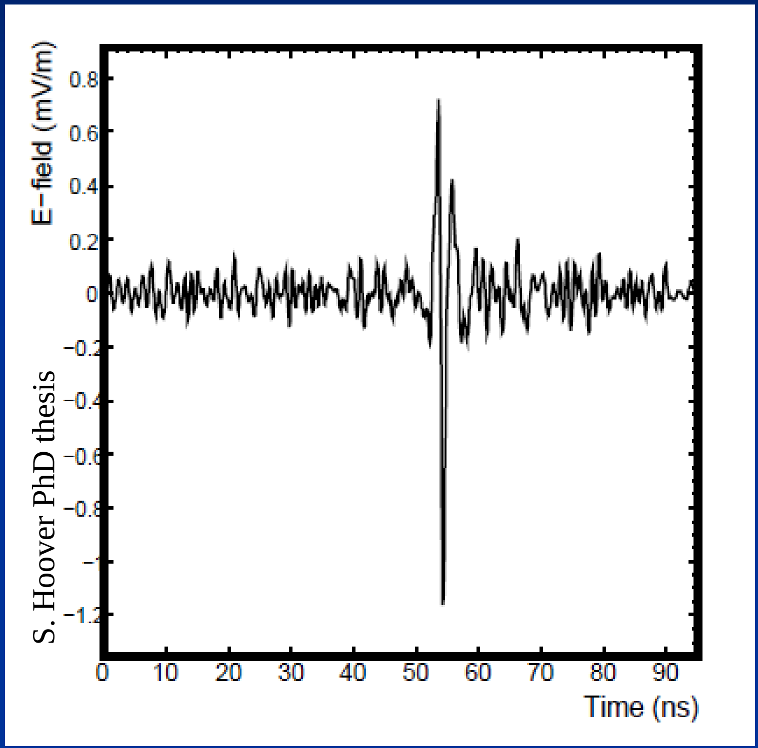
- **Radio "footprint" on ice is a ring for n≠1.**
- **Relativistic effects:**
  - **Inside the ring, the time is reversed – the observer sees the end of the shower first**
  - **For the observer anywhere on the ring the shower happens instantaneously – "Relativistic amplification"**
- **The opening angle for the ring is ~1° degree**
- **From what part of the ring the signal seen by ANITA is reflected?**
- **ANITA data have degeneracy in azimuthal angle (φ polar coordinate)**
- **How far from the shower core the signal is seen (r polar coordinate)?**



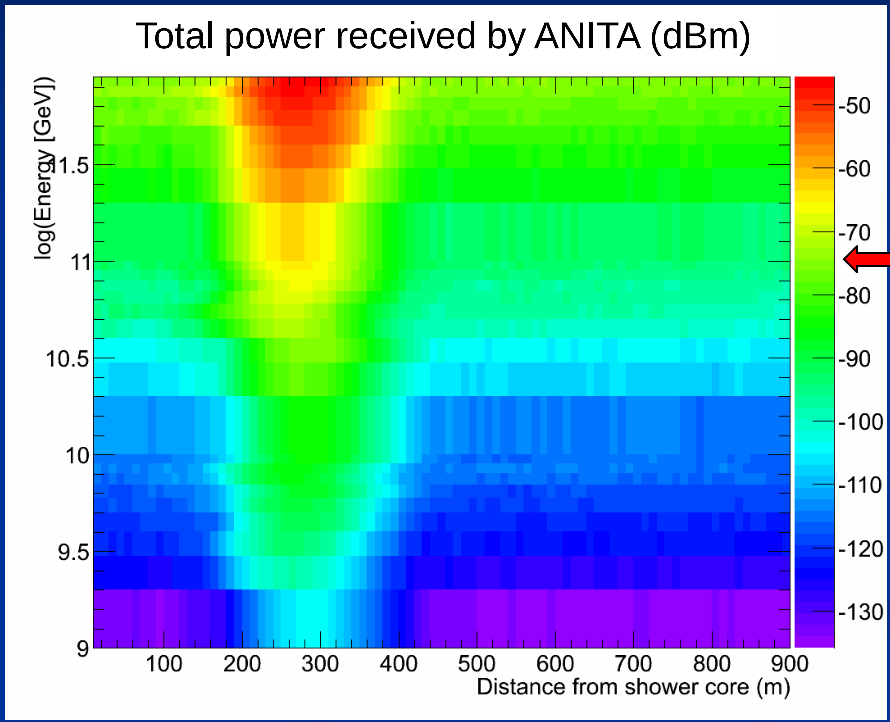
H-pol component of E-field on ice
at the time of maximum E-field magnitude.

Total power in RF received by ANITA

ANITA data. Sample event
Instrument response decovoluted



MC Simulations for ANITA sample event at different energies

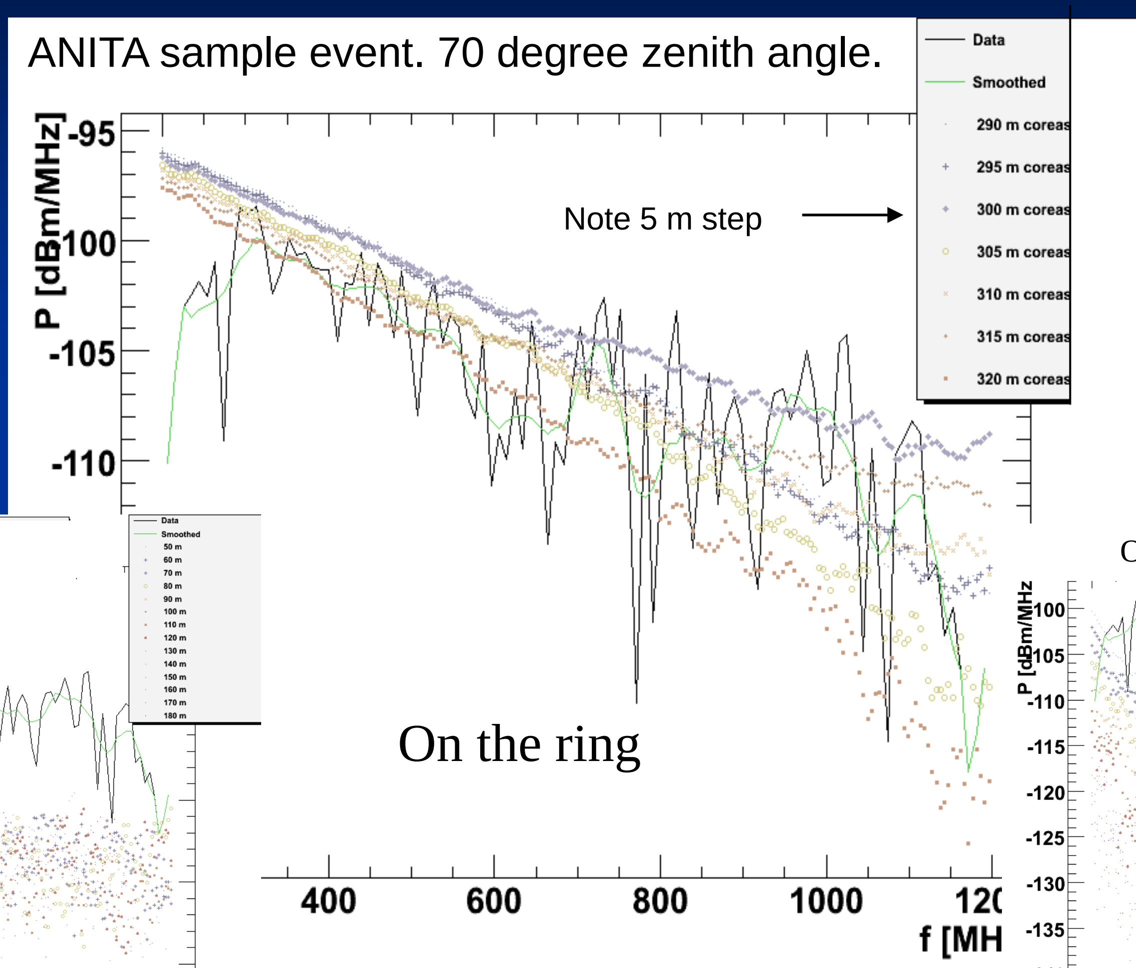


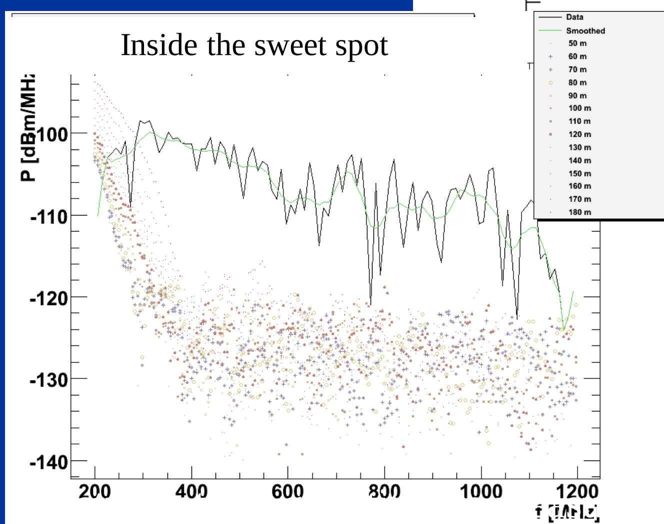
Total power in RF received by the payload from air showers of different energies reflected at different distances from the shower core.

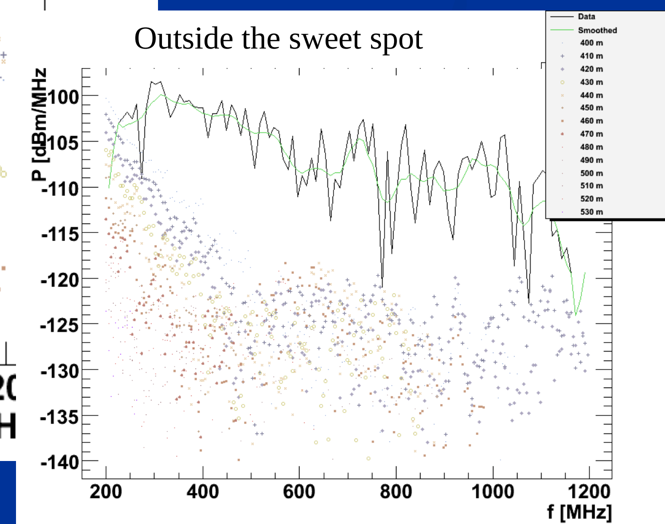
1/r, Fresnel, roughness, antenna response are accounted for.

Total RF power is not enough to reconstruct the primary particle energy

Use the event spectrum to get the upper limit on the primary particle energy







f the spectral index

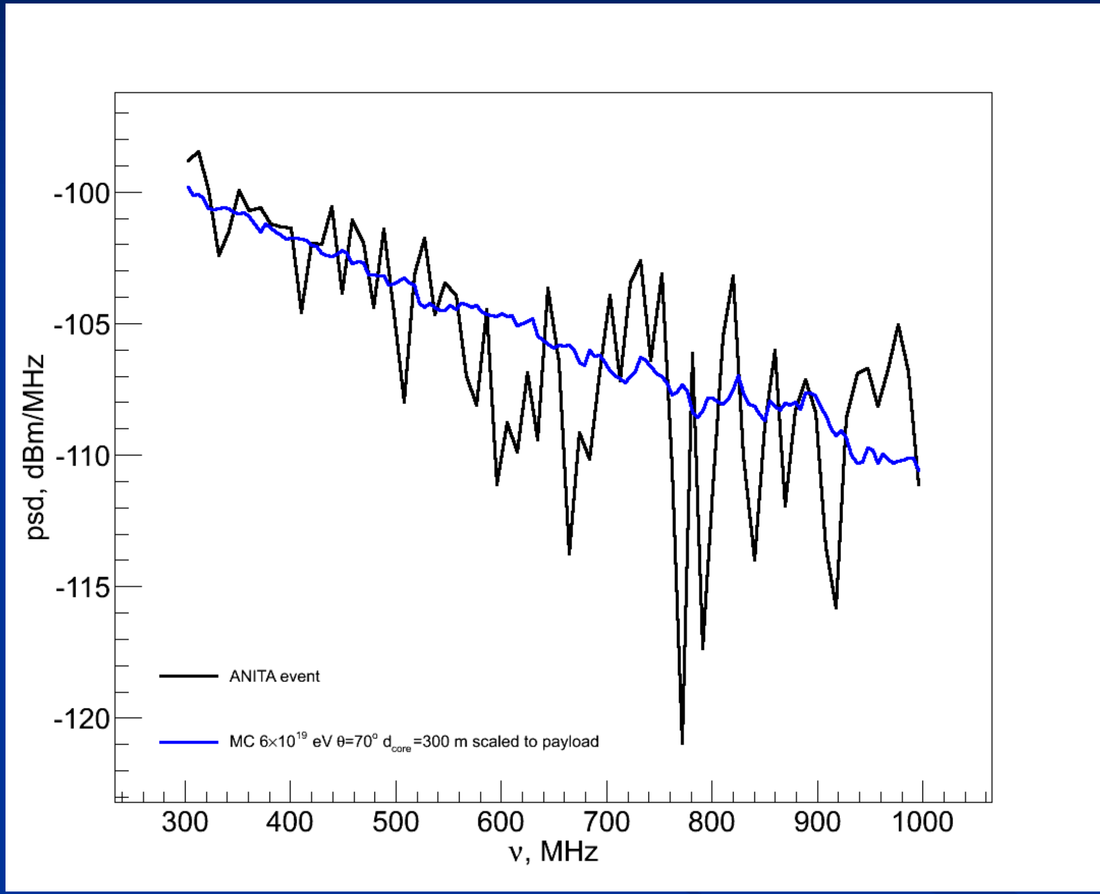
- We are sensitive to about 5 -10 m difference from the shower core.
- Black – ANITA I data. Green – smoothed ANITA I data.
- Spectral ratio is a quantitative measure of the RF signal spectrum.

$$R = \frac{P_{(300-650)MHz}}{P_{(650-1000)MHz}}$$

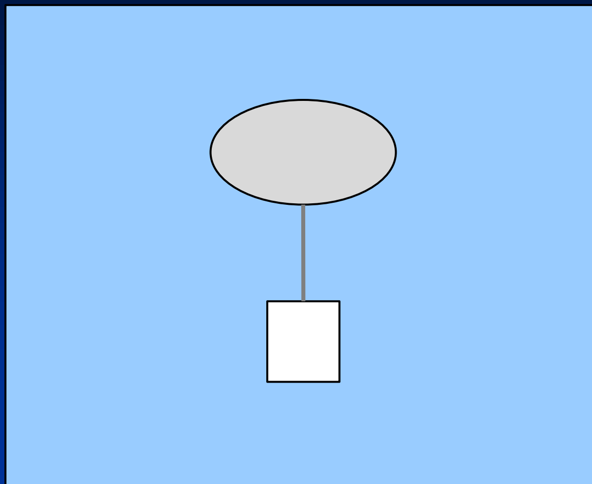
Match the observed spectrum to MC simulation

- **Combine spectrum information with total power to obtain energy**
- **ANITA I trigger was optimized for neutrino – there is trigger bias for CR events**
- **Most of the observed events reflected from the top of the Cherenkov cone**

MC simulated spectrum matched to the ANITA event



ANITA III – Dec 2013 – ?

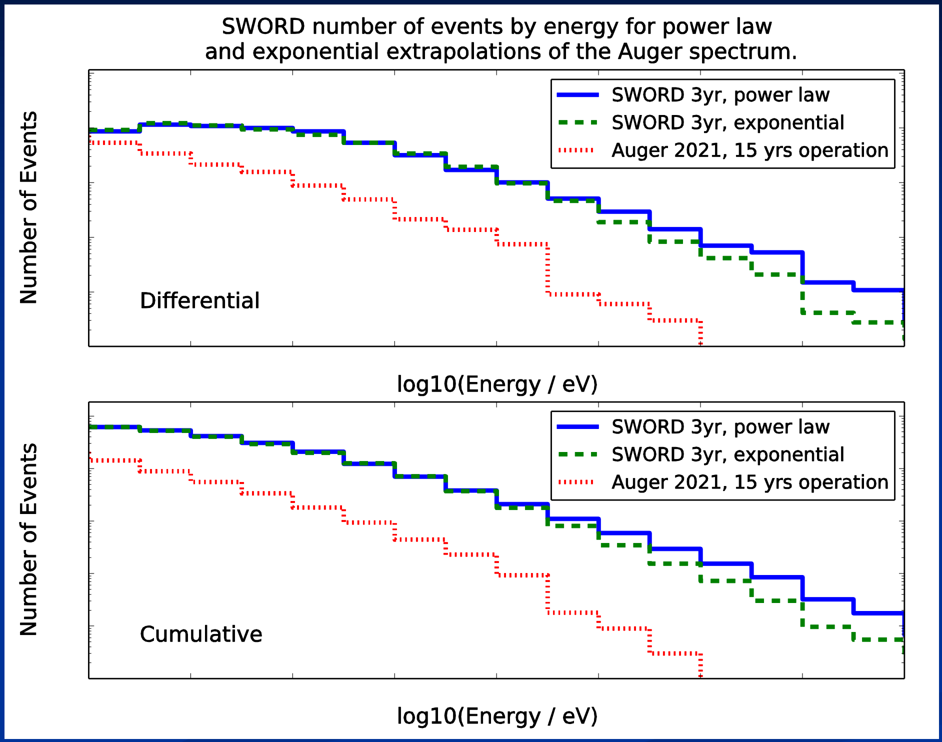


?

- **H-pol trigger optimized for UHECR's**
- V-pol trigger optimized for neutrino
- A dropdown lower frequency H-pol antenna to increase CR aperture
- New DAQ system

K. Belov UCLA

UHECR Radio Detector in Space (SWORD)



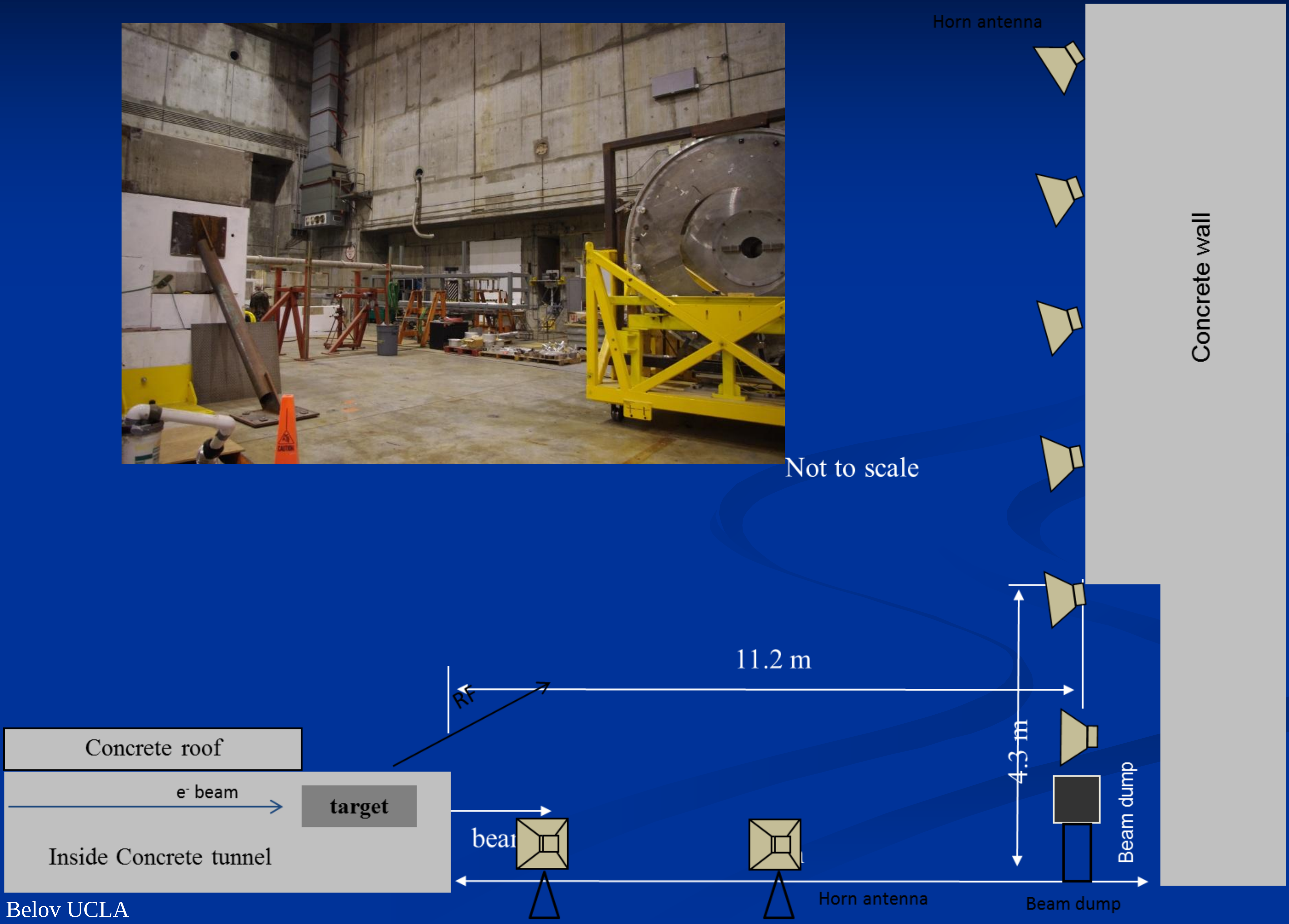
A.Romero-Wolf, P.Gorham, K.Liewer, J.Booth, R. Duren
arXiv:1302.1263

- The synoptic wideband orbiting radio detector (SWORD)
- Very large aperture, but many challenges to overcome:
  - Atmospheric de-dispersion for hardware trigger
  - Energy calibration
  - Deployable antenna design

RF calibration

- UHECRs energy and X_{max} measurements by a balloon, space or a ground instrument rely on MC simulations.
- Several Monte Carlo codes are under development now
  - full MC: CoREAS, ZHaireS – no assumption about radio emission mechanism
  - Macroscopic models EVA, Dave Seckel's model
- MC need to be validated by an experiment in controlled lab environment. An experiment in ESA at SLAC has recently been approved:
  - Proposal "Geosynchrotron emission from extensive air showers" - http://www-conf.slac.stanford.edu/estb2012/talks/KBelovSLAC_20120823.pdf (1st ESTB user meeting, Aug 2012)
- A new radio detector array on the ground:
  - Will significantly improve the results achieved by earlier RF measurements on the ground
  - broadband antenna(s) and DAQ system allow to reduce the antenna spacing on the ground to ~ 50m, longer base is fine for lower frequencies
  - At the site of well established air fluorescence or/and ground counter array (TA or Auger) for cross-calibration

Geosynchrotron emission from extensive air showers. End Station A building at SLAC



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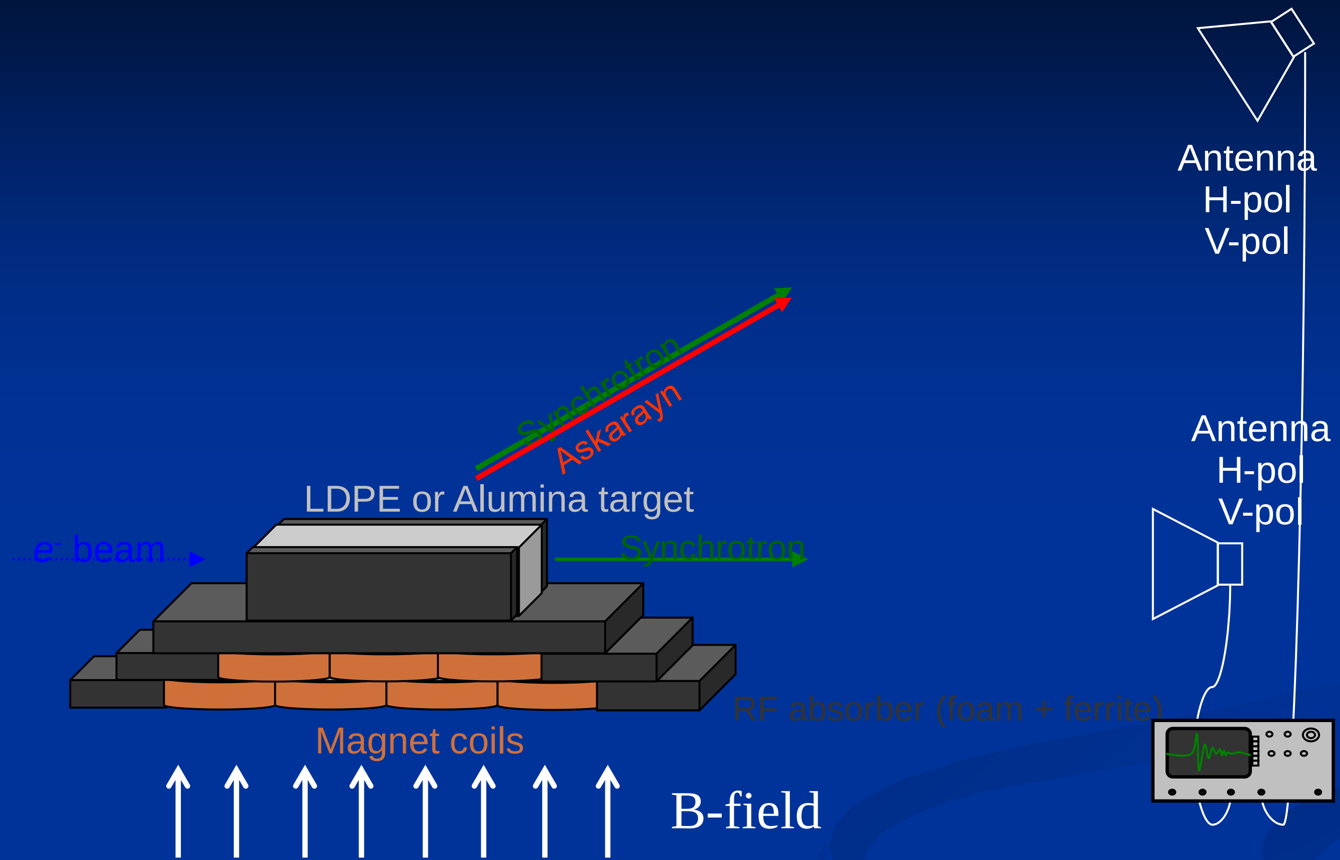
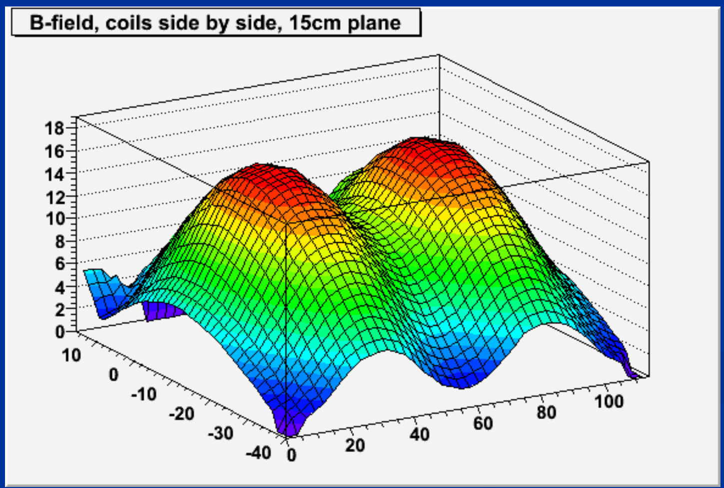
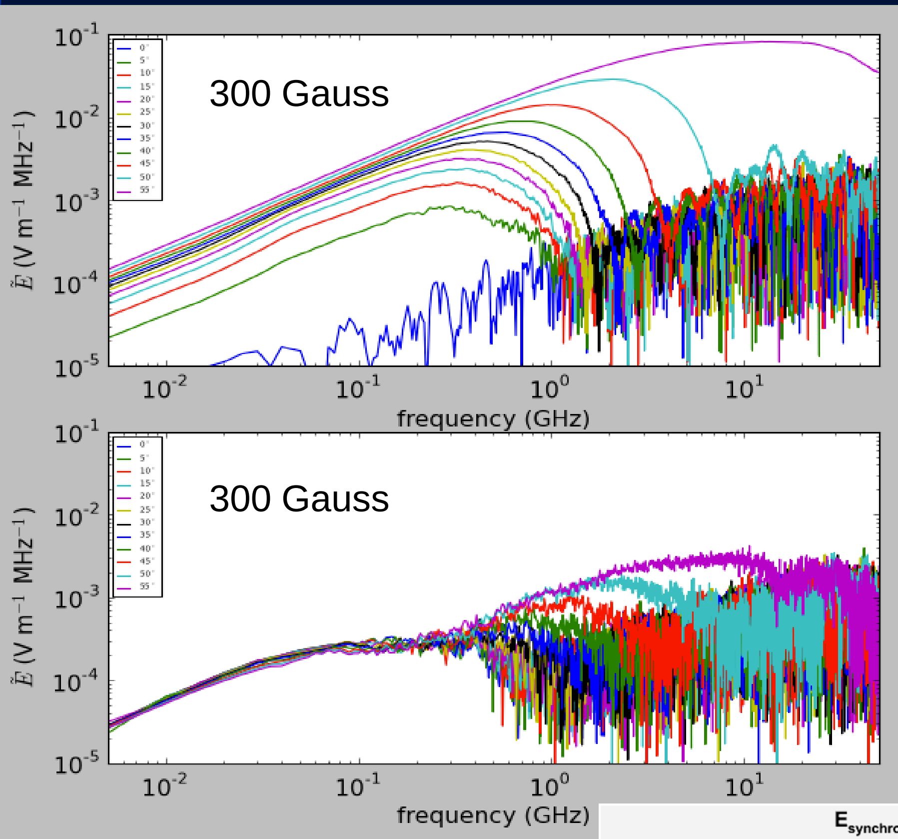
Target design





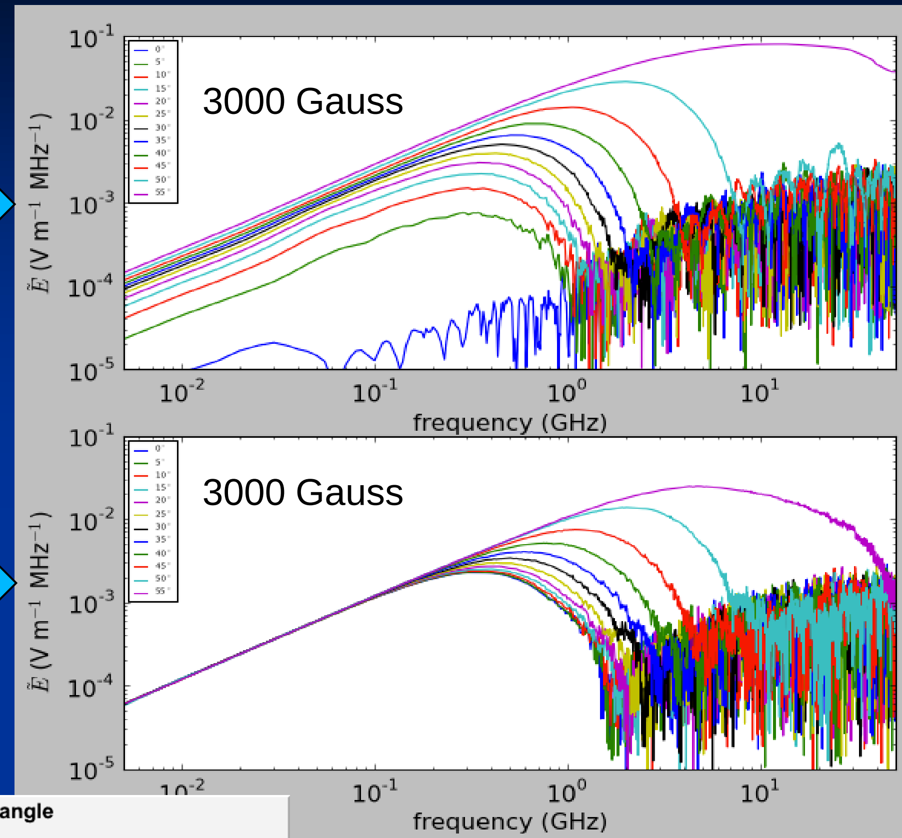
B-field from two coils side by side

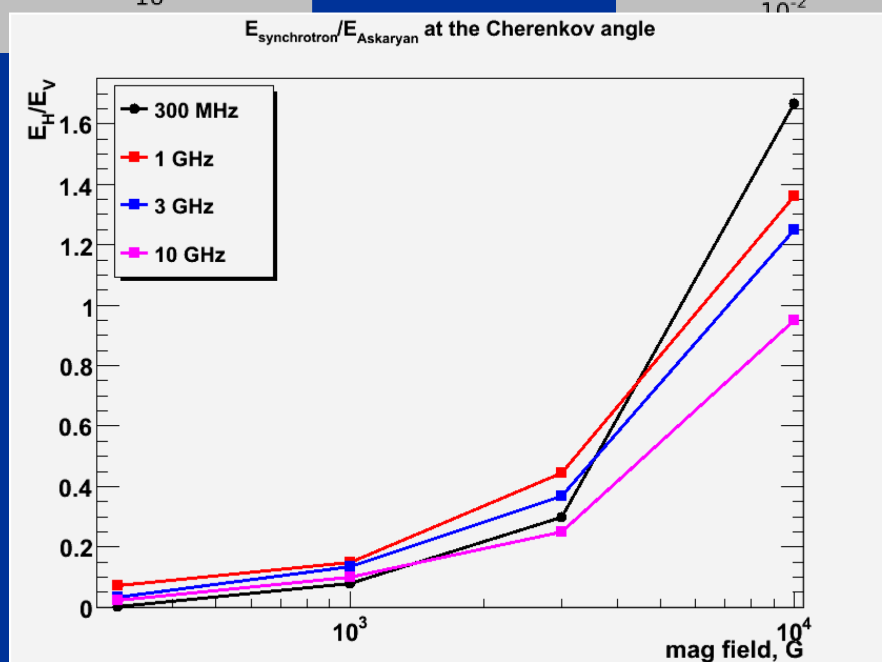
Spectra at different angles



Askaryan

synchrotron



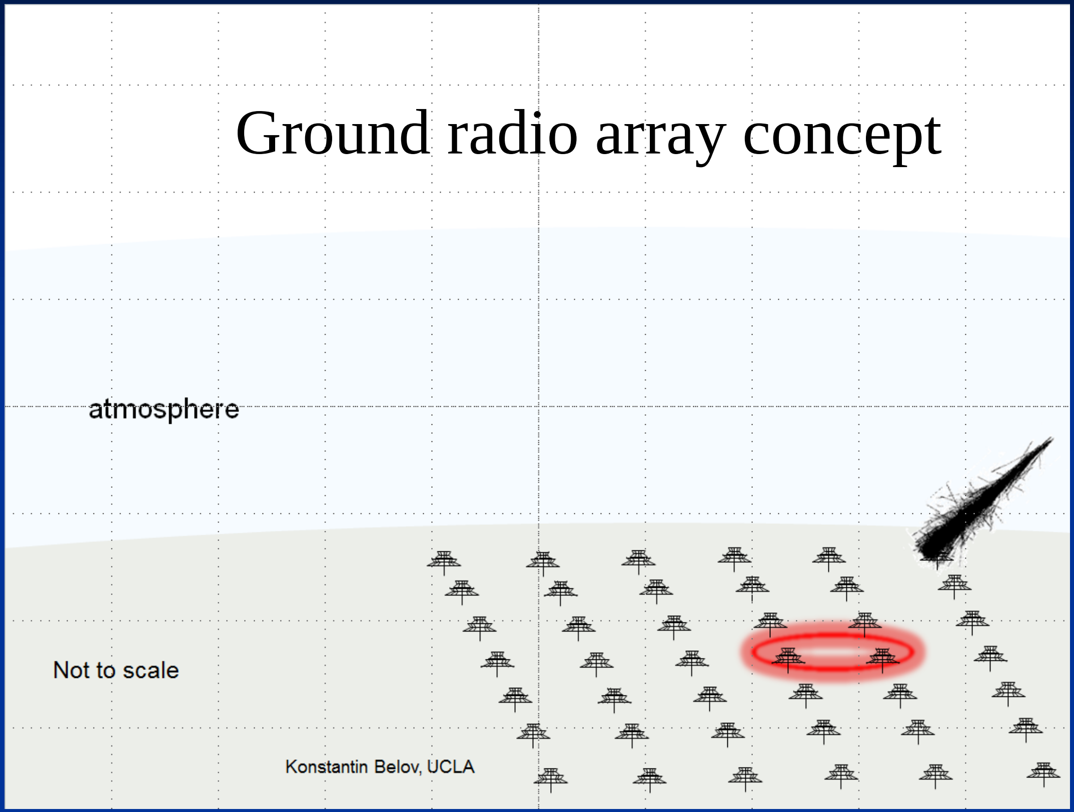


Upper plots by Andres Romero-Wolf

GEANT4 + ZHAireS simulations. Alumina (n=1.73) filling the entire space

The ratio improves significantly for a less dense medium such as polyethylene.

Ground Radio Array



- Early attempts started in 70s
- ANITA balloon-borne detector demonstrated a possibility of UHECR observations in radio
- We now have much better understanding of the RF emission combined with new analysis techniques

- Very simple broadband antenna design
- Antenna spacing depends on the frequency range
- Spectral analysis technique allows to increase antenna spacing => lower the deployment costs
- Can measure the primary particle energy and X_{max} of the extensive air shower by reconstructing the Cherenkov ring on the ground
- Energy calibration or a stand alone UHECR observatory

Conclusions

- **A significant progress has been made in the last year in understanding the radio emission mechanism of the UHECR's**
  - **K. Belov, "*Radio emission from Air Showers. Comparison of theoretical approaches*", to appear in proceeding for ARENA 2012 workshop, Erlangen, Germany** **https://indico.cern.ch/getFile.py/access?contribId=22&sessionId=9&resId=0&materialId=slides&confId=159364**
- **RF data can be used to obtain the energy of the UHECRs. Spectrum measurement is a must**
- **The RF footprint on the ground carries information about the extensive air shower development => composition and cross-section studies**
- **In addition to accelerator measurements, we need a large ground broadband radio array, preferably at the location of existing cosmic ray observatory (Auger or TA)**
- **New MC and reconstruction technique allow energy and X_{max} measurements by a stand alone broadband radio array.**
- **Radio technique will allow us to get more data at highest energies and finally solve the mystery of the cosmic rays that holds ground for too long!**